

DEVELOPMENT OF THE LABORATORY ANAEROBIC BIOREACTOR FOR WET AND DRY DIGESTION PROCESSES

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Abstract

This article presents partial results of the laboratory development of an anaerobic bioreactor designed for the physical modelling of (semi)continuous dry or wet anaerobic digestion processes. A horizontal cylindrical tank reactor of 0.4 m³ total capacity has been developed. The reactor allows the continuous stirring of a liquid batch or the intermittent stirring of a solid batch. The bioreactor has been used as a lab-scale digester in the research project dealing with high-solids (dry) anaerobic co-digestion organic fraction of mixed municipal solid waste. The first experiment was performed on the mixture of MSW with corn silage (1:1) with the weight of 300 kg.

Key words: anaerobic digestion, dry process, wet process, physical model, continuous stirring.

1 INTRODUCTION

Within the project of the Technology Agency of the Czech Republic no. TH01030513 (Epsilon program) under the acronym "GEWA" and title "*Research on High-Solids (Dry) Anaerobic Co-Digestion Organic Fraction of Mixed Municipal Solid Waste with Other Organic Waste and Development of (Semi)continuously Operating Container Biogas Plant with Batch Re-Layering System*", it was necessary to develop a laboratory model of an anaerobic bioreactor for physical modelling semicontinuous anaerobic digestion at high dry matter (total solids) content in a reaction mixture (dry process). The process will be applied in the industrial scale contained anaerobic bioreactor GEWA whose development was initiated.

The GEWA bioreactor is conceptually based on the patented and long term successful production of the EWA (*Ecological Waste Apparatus*) aerobic fermenter from the company AGRO-EKO Ltd. EWA is the mobile unit of a composting machine built in a standard ISO shipping container 1AAA (length 40') [1]. In comparison with other systems, the reacting mixture of biomass (compost pile) in the EWA fermenter can be continuously or periodically stirred [2]. Stirring takes place as biomass re-layering using a bucket conveyor system, fold-over cutters forming a cross-split floor and a cross-split bulkhead ceiling. The original idea for the GEWA reactor was to preserve this interstratification system for biogas producing an anaerobic batch to allow a more intensive course of digestion compared to common dry biogas reactors of a "garage type". The GEWA container will be designed for small farmers, food producers, hotels, biowaste collection points, etc. to enable them energy self-sufficiency and waste recycling.

2 BIOREAKTOR DEVELOPMENT

The laboratory model of the GEWA anaerobic bioreactor using a bucket conveyor for mixing about 300 kg solid batches has been developed at a theoretical level. In the first half of the year 2015, basic schematic drawings and a balance sheet of costs were prepared. Due to the reduction in grant funds and high time demand it has been necessary to withdraw this model from the production.

As a viable alternative, a model has been developed on the basis of a horizontal cylindrical reactor with an axially mounted paddle stirrer (Continuously Stirred Tank Reactor) that has already been partially prepared.

2.1 The requirements

The model is subject to the following requirements:

- 300 kg of a solid batch,
- Working temperature regulated in the range of 30-70°C, with a maximum deviation of $\pm 2^\circ\text{C}$ in individual areas of the batch,
- The time-adjustable stirring of the batch with the possibility of continuous operation,
- Manual batching daily doses of substrates through a vertical pipe,
- The possibility of an additional automatic dosing system connection through a horizontal pipe,
- The manual removal of daily doses of digestate using a short vertical unloading screw.

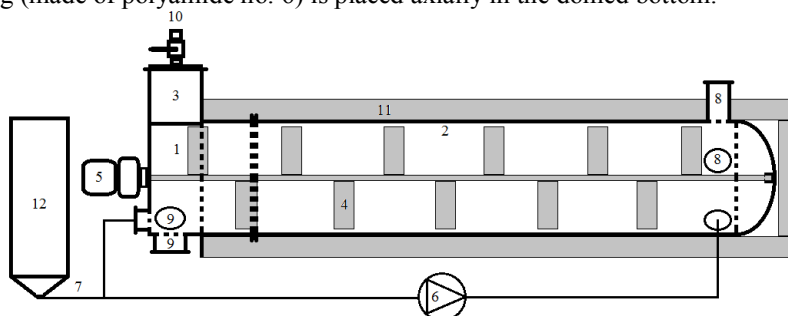
2.2 Prototype bioreactor description

Material

The laboratory prototype bioreactor marked CSTR 400 is made of normal structural steel (reactor forehead with biogas trap, reactor tube) and stainless steel AISI 316 (steel frameworks, paddle stirrer). The rubber seals are made of oil resistant nitrile butadiene rubber (NBR).

Reactor

The reactor (see Figure 1) consists of a technological forehead (500 mm in diameter), which is screwed through the rubber seal with a cylindrical part (tube) ended by a welded domed bottom (500 mm in diameter). The total volume is 0.400 m^3 , wherein the working volume of the batch is 0.300 m^3 . The technological forehead passes in a vertically positioned gas collection space (biogas trap 0.020 m^3). The outlet biogas valve is not influenced by foam or biomass crust. The technological forehead includes a gas-tight bushing (ball bearing and 4 simmerings) for the axially placed shaft paddle stirrer and asynchronous electric motor with a front gearbox. The second bushing (made of polyamide no. 6) is placed axially in the domed bottom.



1 – technological forehead	7 – liquid substrates input from dosing vessel
2 – reactor tube	8 – solid substrates input
3 – biogas trap	9 – digestate output
4 – bidirectional paddle stirrer	10 – biogas output
5 – electric motor	11 – thermal insulation
6 – bidirectional dosing and recirculation	12 – dosing vessel

Fig. 1 Bioreactor basic scheme.

Paddle stirrer

The stirrer (agitator) consists of a hollow stainless steel shaft, 30 mm in diameter, and 11 screwed paddles. The paddles extend to a distance of 10 mm from the reactor wall and are mutually displaced by 90° in order to form an imaginary spiral around the shaft. Each blade is tilted against the direction of rotation by an angle of 45° . Thus, a pressure is applied to achieve a horizontal movement of the batch. The three-phase asynchronous motor (180 W) with the front gearbox is cooled by an integrated fan (20 W).

Pump

Given that the structure of the CSTR reactor does not preclude its use with a liquid batch (for wet digestion process), the model is provided with a pump, an inner diameter DN65, a coaxial flexible (rubber) impeller allowing reversible operation. The pump is triggered manually or using a relay with variable operating time and pause time. Solid particles in a liquid batch may reach the size of up to 20 mm.

Substrates dosage

Solid substrates are fed into the reactor either manually – through the vertical pipe DN100 (after removing the clamp and lid), or automatically – through the horizontal pipe DN100. Both pipes mouth near the domed bottom of the reactor. During very short term manual dosing, a slight leakage of biogas or slight aeration occurs. In terms of safety or in terms of biogas production measurement accuracy this is not a problem. Both, the pipe screw conveyor and the piston system for automatic solid substrates dosing are in development. These systems should work without biogas leakage or aeration. Liquid substrates such as cattle slurry may be dosed with a pump (after connecting a dosing vessel through the ball valve). If the dosing vessel allows mixing, solid substrates can be added to slurry.

Batch stirring (agitation)

The paddle stirrer is triggered manually or using a running relay with variable operating time and pause time. In the setting (I), the stirrer rotates clockwise (seen from the head of the reactor). Then the tilted blades ensure a slight batch particles shift away from the domed bottom (from the dosing pipe) to the technological forehead (to the digestate outlet). In the setting (II), the stirrer rotates counterclockwise and the batch is shifted in the opposite direction.

The second method of agitation uses batch pump recirculation. A liquid batch with less than 10 wt. % of total solids can be circulated continuously. A semi-dry batch with up to about 18 % wt. can be circulated intermittently. In the dry process, the pump is not used. In the setting (1), the pump sucks the batch from the right side of the domed bottom and pushes it through the outer DN65 hose line into the bottom part of the technological forehead. There the batch flow cleans the digestate outlet. In the setting (2), the pump recirculates the batch in the opposite direction.

Digestate removal

The solid residue can be removed after the dry digestion process (solid digestate) from the reactor at the bottom of the forehead using three methods:

- a) Using a vertical screw unloader with a hand-operated crank,
- b) Inserting a rubber plunger into the horizontal pipe (DN80) with a manual displacement of the digestate through the opposite pipe (DN100),
- c) By simple manual pulling the digestate out of the DN100 tube.

In each of the methods, a slight leakage of biogas or slight aeration occurs. The liquid digestate can be drained through the DN65 ball valve or it can overflow the DN65 siphon. Another possibility is pumping the liquid digestate into the external vessel.

Heating System

The bioreactor is tempered to the operating temperature by means of up to six resistive electrical heaters originally intended for heating 3D printers. The heaters are connected to the outside of the reactor tube and powered by up to six switching power supplies (12VDC/12 A). The power supply cabinet is located next to the reactor. The thermostatic control is performed by means of six thermocouple probes in the range of 5 °C above ambient to 70 °C. The operating temperature is typically set to 40 ± 2 °C or 55 ± 2 °C. By changing the combination of active thermocouples and their location, temperature equalization throughout the volume of the batch can be achieved. The reactor is thermally insulated using panels of expanded polystyrene foam (100 mm in thickness). The insulation forms a container. Only the front part of the technological forehead with the biogas trap is left without insulation. Photographs of the reactor are shown in Figure 2.



Fig. 2 Laboratory bioreactor in development.

3 FUNCTIONAL TESTING

The model bioreactor has been tested for gas tightness at overpressure of 1 and 3 atm. Then, a leak test was done with 0.300 m³ of clean water and air overpressure of 3 atm. The screw and clamp joints had to be tightened. Subsequently, the test operation was carried out with a liquid batch (0.300 m³ of cattle slurry with 8% wt. of total solids content). The total solids content was gradually increased by adding corn silage and sawdust of up to 18 wt. % (upper limit for a given type of pump). During the test, there were no problems with the paddle stirrer.

The test operation with the solid batch was initiated by filling the empty reactor with 100 kg of fresh compost with 50 wt. % total solids content. The engine still managed to propel the stirrer. Gradually, the solids content has been decreased by adding water to 20% wt. (lower limit for dry digestion process). It turned out that even in the case of stirring a 300 kg solid batch, the paddle stirrer is suitable, but the engine must be replaced with a double performance type and speed has to be decreased below 20 rpm.

Tab. 1 Bioreactor parameters.

Parameter	Unit	Value
Empty weight	kg	250
Total volume	m ³	0.420
Working volume (batch volume)	m ³	0.300
Biogas trap volume	m ³	0.020
Paddle stirrer speed (rpm)	min ⁻¹	24
Electric power for stirrer (400V AC)	W	125
Electric power for heaters (230V AC)	W	900 (6 x 150)
Electric power for pump (400V AC)	W	1000
Typical mode of stirrer operation	s	60 _{running} / 600 _{pause}
Typical mode of pump operation (liquid batch)	s	10 _{running} / 600 _{pause}
Typical power consumption for stirring	kWh/day	0.27
Typical power consumption for liquid batch recirculation	kWh/day	0.39
Typical power consumption for heating	kWh/day	6.25
Estimated gains of primary energy (relative to biogas calorific value)	kWh/day	4 - 30

4 DISCUSSION

Although the dry anaerobic digestion is the established production method of renewable energy and of solids biowaste processing in Europe, North America, and other parts of the world, there are not many links to the development of lab-scale bioreactors for dry anaerobic digestion of biomass with a continuous mode of stirring.

In the dry anaerobic digestion process, mixing is difficult and comparatively expensive as dry reactors have a smaller volume than wet reactors for a comparable organic loading rate [3],[4].

Most systems use non-stirred reactors [5],[6]. A higher volumetric organic loading rate should advantage a high-solids process, but, without stirring, the retention time has to be excessively long [7]. Systems consisting of a horizontal rotating drum [8] provide very good mixing of the batch, but it is difficult to apply it on larger scale. The construction utilizing a horizontal stationary reactor and the stirrer in the shape of screw with a very gradual incline [9][10] is operationally applicable, but the energy requirements for stirring are high. The construction with the horizontal paddle stirrer is a compromise between stirring perfection, energy demand, simplicity and reliability.

5 CONCLUSION

The physical model of the anaerobic bioreactor with a working volume of 0.3 m³ has been developed. The model is adapted for biogas production tests in dry and wet processes, whereby not only a liquid but also a solid batch can be continuously stirred to achieve suitable process conditions for carrying out a semi-continuous process. The dosage of substrates has so far been resolved manually (1x to 2x per day), but the automatic dispensing equipment is in development. The model will be used to verify the high-solids anaerobic process regime for the prepared industrial scale contained bioreactor GEWA. The model is suitable for micro-scale biogas production (1-2 m³ per day) under the conditions of waste heat sources availability and heat exchanger installation.

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